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Fermi Ball Detection

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Abstract

The detectability of charged SLAC-bag type structures is considered. These objects, known as Fermi balls, arise from the spontaneous symmetry breaking of a biased discrete symmetry in the early universe. Two classes of experimental searches are discussed. Since Fermi balls in the theoretically favoured mass range are absorbed by the atmosphere, direct experimental searches are confined to space-based facilities. Simple spectrometer and time of flight analysis give a quantitative estimate of Fermi ball mass up to a limit set by the system's tracking resolution. For the ASTROMAG facility, with a tracking resolution of $50\text{ }\mu\text{m}$ the upper bound on detectable Fermi ball masses is of order $10^{15}\text{ GeV}/c^2$. Charged tracks with sagitta smaller than this resolution would provide evidence in favour of Fermi balls, but only give a lower bound on the discrete symmetry breaking scale φ_0 . The second class of experimental search proposed relies on the detection of bound Fermi ball states that have been concentrated in terrestrial materials such as oceanic sediment.

An analysis of biased discrete symmetry breaking in the early universe has indicated the possibility of production of composite particles called Fermi balls[1]. These Fermi balls are formed out of collapsing fermion-populated domain walls that are generated as the result of spontaneous symmetry breaking of a biased discrete symmetry associated with a real scalar field. A strong Yukawa coupling of generic fermions to this real scalar field insures that fermions are swept up by, and stay within, the domain walls as they collapse upon themselves, thereby forming finite sized false vacuum bags enclosed by a fermion populated domain wall skin.

These false vacuum bags collapse and fragment until the soliton nature of the bag structure arrests the collapse. Conceptually, this halting of the collapse is a result of the Fermi gas pressure of the domain wall fermions balancing the false vacuum volume pressure and domain wall surface tension. In the bag model description of the Fermi ball this may occur when the thin domain wall approximation breaks down. The structure that emerges is one of numerous composite particles (Fermi balls) each composed of massless fermions contained in a supermassive SLAC bag like construct with a radius (in GeV^{-1})

$$R_{FB} \sim \frac{2}{\varphi_0} \quad (1)$$

and a mass of approximately $100\varphi_0 \text{ GeV}/c^2$ where, φ_0 (in GeV) is the symmetry breaking scale. Hence, the Fermi ball mass is dependent on the discrete symmetry breaking scale parameter φ_0 .

The spontaneous symmetry breaking of a biased discrete symmetry is not in itself sufficient to produce cosmologically stable Fermi balls. Such objects can only exist if there exists a net fermion antifermion asymmetry. As the domain wall confinement of fermions prevents fermion number freeze out, a Fermi ball would be completely deflated by fermion pair annihilations if there was a fermion antifermion symmetry. Assuming a fermion antifermion asymmetry, these cosmologically stable Fermi balls can carry a standard model gauge charge which depends on the fermion content of the individual Fermi ball.

Conservative constraints on the neutral Fermi ball mass and cross section have already been given in [1]. We focus on the detection of Fermi balls with overall standard model gauge charges, and for simplicity consider the case of an electric charge equal to the sum of the charges of the Fermi ball fermion population. A specific Fermi ball charge prediction can only be the result of a detailed study of fermion-antifermion asymmetries just prior to discrete symmetry breaking,

subsequent domain wall formation, and fermion evaporation and reabsorption. In order to minimise assumptions as to extent of fermion antifermion asymmetry in the early universe we allow for a Fermi ball charge ranging from $-Ne$ to $+Ne$, where N is the number of massless fermions contained in the Fermi ball – $N \sim 50$ [1], independent of the breaking scale. If more than one fermion type is present, such a mixture of fermion species would only serve to reduce the Fermi ball charge from the maximum allowable charge ($\pm Ne$).

Fermi ball production is the result of the collapse and fragmentation of false vacuum bubbles encased in fermion populated domain walls into massive remnants. Consequently, assuming no special acceleration mechanisms are operating, one would expect the typical Fermi ball velocity to be of the order of the average galactic velocity $v \sim 250$ km/s, or less. For a Fermi ball with a typical velocity of order $10^{-3}c$, the quantitative estimate of the mass required for a maximally charged Fermi ball to penetrate the atmosphere depends on the sign of the charge. Assuming positively charged Fermi balls generate a completely neutralising electron cloud as they pass through the atmosphere, the Fermi ball is analogous to a nuclearite, and has an energy loss per path length given by De Rujula and Glashow [2]:

$$\frac{dE}{dx} = -A\rho v^2 \quad (2)$$

where A is the effective cross-sectional area of the nuclearite, v is its velocity, and ρ is the density of the medium. Thus v , decreases exponentially with distance D , according to:

$$v(D) = v(0)e^{-\left(\frac{A}{M} \int_0^D \rho dx\right)} \quad (3)$$

where M is the mass of the nuclearite. Taking the column density of the atmosphere to be 1013 g/cm², the mass required for the positively charged Fermi ball to penetrate the atmosphere and retain a cosmic velocity ($\beta = 10^{-3}$) is of order 9×10^9 GeV (i.e. $\varphi_0 \approx 10^8$ GeV). Alternatively, negatively charged Fermi balls suffer energy loss due primarily to electromagnetic interactions with atomic electrons, and for such low velocity objects the energy loss calculation is analogous to that for a charged heavy ion undergoing only electromagnetic interactions. An approximate form of the energy loss per path length has been given by Lindhard [3], which assigns no specific structure to the projectile and treats the surrounding atomic electrons as an electron gas of constant density.

Lindhard's model assumes the projectile forms no neutralising cloud, and so for the energy loss calculation, the Fermi ball acts like an ion of atomic number $Z_1 = |Q|$, where Q is the bare Fermi ball charge. The energy loss per path length for such a slow moving negatively charged Fermi ball is then estimated by:

$$\frac{dE}{dx} = -\frac{2m_e^2 Z_1^2 e^4 v}{3\pi\hbar^3} \left(\log \frac{137v_F}{c} + \log \pi - 1 + \frac{2c}{137\pi v_F} \right). \quad (4)$$

where, for a typical detecting medium, the ambient electron velocity is the Fermi velocity v_F , which is of order the Bohr velocity, $v_0 = \frac{e^2}{\hbar} \approx 2.2 \times 10^8$ cm/s $= 7.3 \times 10^{-3}c$. The mass of a negatively charged Fermi ball required to penetrate the atmosphere and retain a velocity between $10^{-5}c$ and $10^{-3}c$ is obtained by evaluation of the mean range $R = \int \frac{dx}{dE} dE$. For a maximally charged Fermi ball this mass is 10^{15} GeV or greater.

The experimental searches considered in this work are divided into two categories: space-based and terrestrial, detection experiments. The choice of two classes of experiment is determined by the fact that unless the charged Fermi balls are extremely heavy, they will range out in the atmosphere. Maximum sensitivity for active searches is obtained using space based experiments, as they offer the possibility of an experimental search over the full range of φ_0 . These space based experiments need only be simple spectrometers, which when coupled with independent time of flight and charge measurements, allow determination of charged particle masses. As the experiment is space based, no neutralising cloud is expected to form around the incident Fermi balls, and so the experiment is sensitive to the bare charge (of either sign).

Suitable experimental facilities, ASTROMAG [4] and WiZard [5], have been proposed. The conceptual layout of ASTROMAG is that of a magnetic analyzer, triggering telescope and a data acquisition system shown schematically in Figure 1. One proposed design for the ASTROMAG facility has a thin superconducting solenoid with coil diameter 2m, a central magnetic field of ~ 1.3 Tesla, and a tracking system resolution of $50\mu m$. Identification of charged Fermi balls is performed by measurement of the sagitta of a charge particle track in the magnetic field. Negatively charged Fermi balls would be particularly distinctive, especially if the magnitude of the Fermi ball charge is maximal. Combined with the independent measurements time of flight information and charge of the particle, the mass can easily be determined. For charged Fermi balls, the signature that is expected is that of a superheavy particle with a velocity of the order of $10^{-3}c$ and a maximum

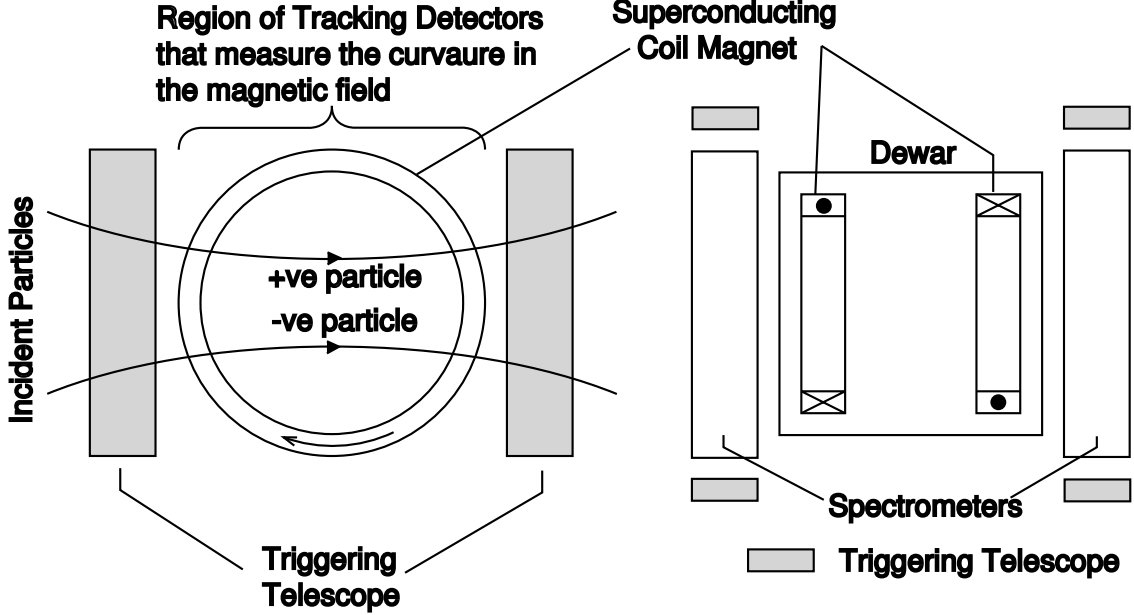


Figure 1: Conceptual technique and layout of the ASTROMAG facility

charge around $50e$ that can be positive or negative. As the Fermi ball is expected to be extremely heavy the sagitta of its track could be less than the resolution of the spectrometer. In this case the charged Fermi ball signature would be that of a non-relativistic charged particle, with positive or negative charge, that produces a track with no measurable curvature. The occurrence of such tracks implies the presence of Fermi ball candidates, but would only allow a lower bound on the discrete symmetry breaking scale, φ_0 (as the Fermi ball mass $M_{FB} \approx 100\varphi_0 \text{ GeV}/c^2$).

The mass range to which the spectrometer is sensitive is explored by plotting the contours of the maximum value of the measurable mass as a function of charge, assuming a uniform magnetic field and a Fermi ball velocity of $10^{-3}c$. Contours which are determined by setting the sagitta to the value of the tracking system resolution give an upper bound on the Fermi ball mass range to which the experiment is sensitive. Several such contours are plotted in Figure 2. It can be seen that for an atomic number of 26 and a tracking system resolution of $50\mu\text{m}$, the maximum identifiable mass by the method of sagitta evaluation is of the order of $\sim 10^8 \text{ GeV}/c^2$ – this corresponds to only a moderate coverage of the breaking scale parameter space : $\varphi_0 < 10^6$. By comparison, the

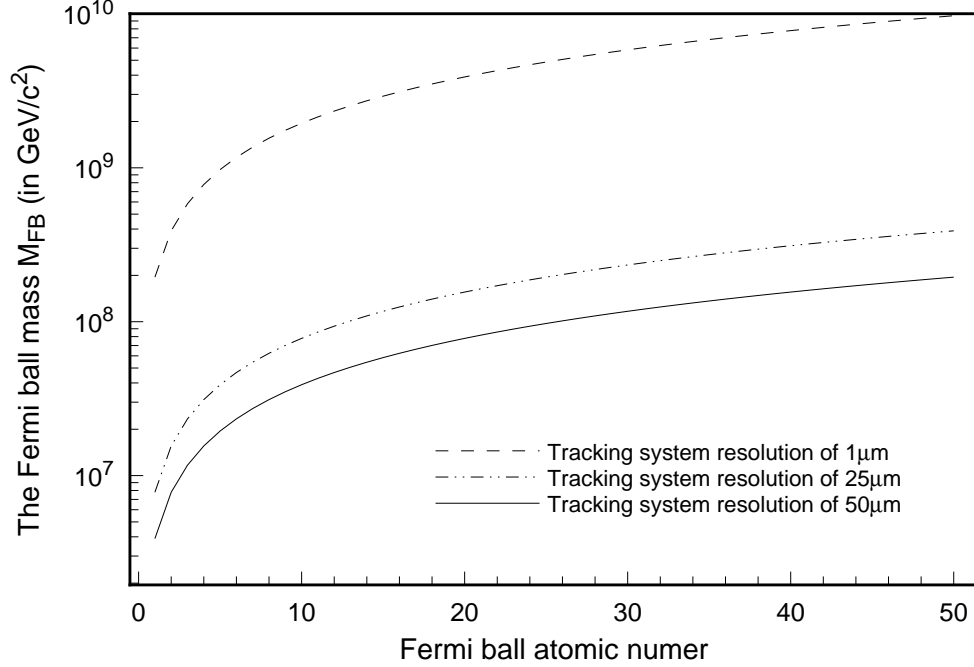


Figure 2: Contour plots of the maximum value of measurable mass, as a function of charge, obtained by setting the sagitta equal to various values of the tracking system resolution. The expected resolution for ASTROMAG is of the order of $50\mu\text{m}$

momentum required by an iron atom to produce a track with a sagitta of $50\mu\text{m}$, equal to the tracking system resolution, is $3 \times 10^{13} \text{ GeV}/c$ – far greater than the value of $0.052 \text{ GeV}/c$ for an iron atom moving at $10^{-3}c$. This example illustrates that when timing and sagitta information are combined the possibility of misidentification of Fermi balls with heavy ions is effectively ruled out.

Any direct Earth based search for charged Fermi balls is only directly sensitive to the extreme end of the φ_0 parameter space. However, there is the possibility Fermi balls that have been stopped in the atmosphere are detectable in passive terrestrial experiments. For example, a positively charged Fermi ball will acquire a neutralizing cloud of electrons as it slows down in the Earth’s atmosphere. These heavy stopped Fermi balls, cloaked with a neutralizing charge, would fall to earth and into the oceans. Fermi balls are characteristically expected to be multiply charged, with a mass $100\varphi_0 \text{ GeV}/c^2$ and a radius which varies as the reciprocal of φ_0 , being ~ 1 Fermi for $\varphi_0 = 1 \text{ GeV}$.

As characteristic breaking scales are substantially greater than 1 GeV we can regard the Fermi ball and its accompanying electrons as a superheavy atom with a maximum Z of about 50e, where the radius of the Fermi ball is typically substantially smaller than 1 Fermi. One possible technique for detecting such an object over most of the possible mass range is time of flight mass spectrometry [6]. In this approach the sample believed to contain Fermi balls, such as ocean sediment, is vapourized with a laser beam and then fully or partially ionized. The time of flight to a microchannel plate, or other suitable charged particle detector, of the fully or partially ionized Fermi ball is then measured. Although, this method does not directly detect the incoming Fermi ball it has the advantage that the possible Fermi ball population in the terrestrial material under test has presumably accumulated over billions of years.

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